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The Air Force Medical Research Laboratory (AFAMRL) has used wind tunnels to conduct research on the problem of windblast protection since 1971. This research has been focused upon the measurement of aerodynamic forces acting on the human body during and after emergency egress from aircraft using volunteer human subjects, anthropomorphic dummies, and scale models. The use of scale models in the wind tunnel has potential problems associated with attempting to create dynamically similar airflows and thus aerodynamically similar forces. Dimensional analysis has shown that the force coefficient for a body of given orientation and shape is a function of the Reynolds number and Mach number provided that parameters such as surface roughness, stream turbulence, and the presence of other bodies in the vicinity are not neglected.

Variations in Reynolds number might cause variations in the type and thickness of the airflow surrounding the crewmember/seat combination. This, in turn, can affect the upstream flow separation point in front of a bluff body such as the crewman/seat, and thereby affect the magnitude of the forces acting on various segments of the body. The influence of these factors must be known when using scale model data for full-scale applications. Therefore, AFAMRL conducted wind tunnel tests using 1/2-scale models to determine the effects of Reynolds number variation on aerodynamic forces acting on a crewmember during emergency escape or after inadvertent canopy loss.

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THE EFFECTS OF REYNOLDS NUMBER VARIATION ON MEASUREMENT OF LIMB FLAIL FORCES AND MOMENTS

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INTRODUCTION. The Air Force Medical Research Laboratory (AFAMRL) has used wind tunnels to conduct research on the problem of windblast protection since 1971. This research has been focused upon the measurement of aerodynamic forces acting on the human body during and after emergency egress from aircraft using volunteer human subjects, anthropomorphic dummies, and scale models. The use of scale models in the wind tunnel has potential problems associated with attempting to create dynamically similar airflows and thus aerodynamically similar forces. Dimensional analysis has shown that the force coefficient for a body of given orientation and shape is a function of the Reynolds number and Mach number provided that parameters such as surface roughness, stream turbulence, and the presence of other bodies in the vicinity are not neglected. Variations in Reynolds number might cause variations in the type and thickness of the airflow surrounding the crewmember/seat combination. This, in turn, can affect the upstream flow separation point in front of a bluff body such as the crewman/seat, and thereby affect the magnitude of the forces acting on various segments of the body. The influence of these factors must be known when using scale model data for full-scale applications. Therefore, AFAMRL conducted wind tunnel tests using 1/2-scale models to determine the effects of Reynolds number variation on aerodynamic forces acting on a crewmember during emergency escape or after inadvertent canopy loss.

METHODS. In order to determine the Reynolds number effects on the aerodynamic forces acting on a crewmember/ejection seat combination, an existing half-scale man/seat model used with a half-scale model of the forward portion of the F-16 and tested in the Arnold Engineering Development Center (AEDC) Propulsion Wind Tunnel (PWT) Facility Transonic Wind Tunnel (16T). The steady-state forces and moments acting on the crewman's limbs and neck, in and near the F-16 cockpit were measured during a simulated ejection sequence. Measurements were taken beginning with the crewman/seat model positioned in the full down, pre-ejection position in the cockpit and then repositioned at intervals of 15.2 cm (half-scale) until seat/rail separation had occurred. All measurements were made with two forebody-model configurations. These consisted of the basic F-16 forebody model and the basic forebody model with flow deflectors mounted above the cockpit instrument panel. Both pitch and yaw angles were 0 degrees. Mach numbers of 0.4, 0.6, 0.8, 1.0, and 1.2 were investigated. Freestream Q was varied from 4.79×10^3 N/M^2 to 2.87×10^4 N/M^2 (100 psf to 600 psf). The range of Reynolds numbers was 1.4×10^6 through 6.9×10^6 based on the reference length of the crewman. Determined from the collected data were the upward force on the helmet, sideward force on the helmet and drag force on the helmet; sideward force acting on the knee, vertical force at the knee; lifting force of the foot, sideward force at the foot; sideward force on the hand at the ejection initiation handle, back force on the hand; sideward force acting at the elbow, drag force at the elbow; force area and moment volume coefficients for all determined forces and moments. Data were also recorded from six model-mounted, high-frequency response, pressure transducers located in the forebody cockpit area.

RESULTS AND DISCUSSION. Flow are considered to be dynamically similar if: 1) they are geometrically similar and 2) if the forces acting in one flow system are in the same ratio to each other as similar forces in the second system. Among the forces encountered in the airstream are those due to inertia, viscosity, gravity, pressure, surface tension, and compressibility. When inertia and viscous forces govern the flow behavior of the compressible airstream, physical laws require that the Reynolds number and the Mach number be the same for both scale and full-scale systems. Reynolds number is defined as

$$Re = \frac{\text{Inertia force}}{\text{Viscous force}} = \frac{\rho V D}{\mu}$$

where ρ = density of air, V = velocity,
D = characteristic dimension, and
μ = viscosity of the fluid.

When using scale models in the wind tunnel, the size of the body being tested is reduced from the full-scale version and correspondingly, the Reynolds number is also reduced. To keep Reynolds number representative, an experimenter can increase the density of the airstream or increase the speed of the airstream to compensate for "scale" effects. For example, if a 1/10-scale model were used in wind tunnel experiments, to properly simulate the airflow conditions encountered in full-scale flight, the Mach number and Reynolds number would have to be the same for both the full-scale and 1/10-scale conditions. In order to keep the Reynolds number the same, if ρ and μ remain constant, a 1/10-scale model would require an airstream 10 times the speed of its full scale counterpart. Using a Reynolds number that is not representative of full-scale produces changes in airflow characteristics which can modify force measurements made with scale models in the wind tunnel (Figure 1).

Bodies that are not geometrically similar will react differently when placed in the same

airstream. Variation of force coefficients with changing Reynolds number will be different for different shapes and objects in the airstream. The head/helmet combination, for example, might react as a sphere in a flow condition whereas the leg, shaped more like a cylinder, would exhibit markedly different flow characteristics.

To determine the variation of flail initiating forces due to Reynolds number effects, all data were converted to coefficient form. This conversion is required since higher Reynolds number flow conditions are developed at higher freestream dynamic pressures. Therefore, all measured airloading is of greater magnitude at higher Reynolds numbers. Reducing the data to coefficient form allows changes due to the influence of Reynolds number to be identified.

Representative body pressure coefficient data are presented in Figure 2. The data indicate that there are no differences in the magnitude of the pressure coefficient data for the ejection position at which the pressure coefficient is measured for different values of dynamic pressure. This indicates that there is no Reynolds number influence in the airflow region outside the cockpit (far field) or in the airflow region around the crewman seat including the area of the cockpit (near field). Since Reynolds number was the only variable changed between comparison runs, any changes in coefficient data must be attributed to changes in the far field, changes in the near field, and/or changes in the local flow on the model itself. These latter changes would be similar to the local change in boundary layer flow and local flow separation on a cylinder or sphere due to Reynolds number changes (Figure 1).

The shear flow condition 80% up the rails is considered the critical case for examining variations in measurement due to Reynolds number since the shear boundary between the cockpit cavity flow and the external flow is small and most sensitive to any flow field changes. Any flow field change would be expected to be marked at this position. Since changes in all of the pressure coefficient data were negligible, it is concluded that the far field and near field flows did not change with changing Reynolds number.

Figure 2 shows the leg pressure transducer traversing an airflow field from cavity flow conditions (fully within the cockpit) to shear flow (80% out of the cockpit) to stagnation flow condition (seat/rail separation) with no change in local pressure coefficient.

Crewmember force area coefficient data, however, showed substanial Reynolds number effects. Helmet lift force area data are presented in Figure 3. The coefficients presented represent half-scale values (to obtain full-scale values, these factors must be multiplied by a factor of four). The coefficients show an increase of approximately 40% when testing at a dynamic pressure of 1.43×10^4 N/M^2 (300 psf) versus 2.87×10^4 N/M^2 (600 psf). This trend is not indicative of all the data, however, and in most instances the opposite of the general trend. Since the far field and near field airflow did not change with Reynolds number, the changes in crewman/seat stability and component data must be attributed to changes in local flow boundary layer around the legs, arms, and head resulting in changes in coefficient data with Reynolds number similar to that experienced on cylinders and spheres.

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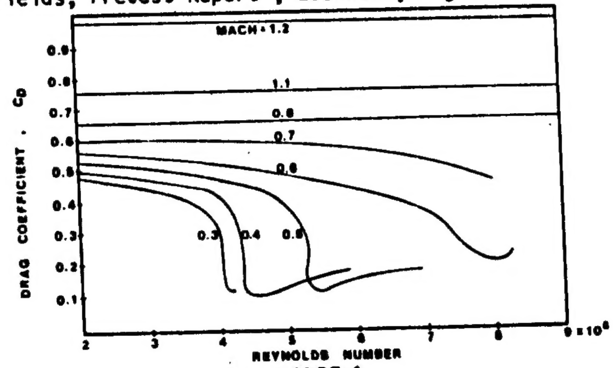

FIGURE 1

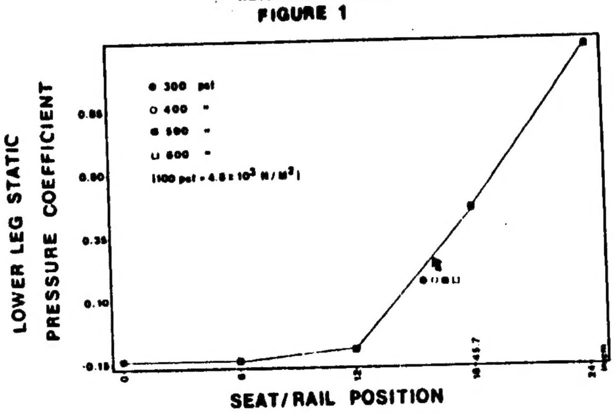

FIGURE 2

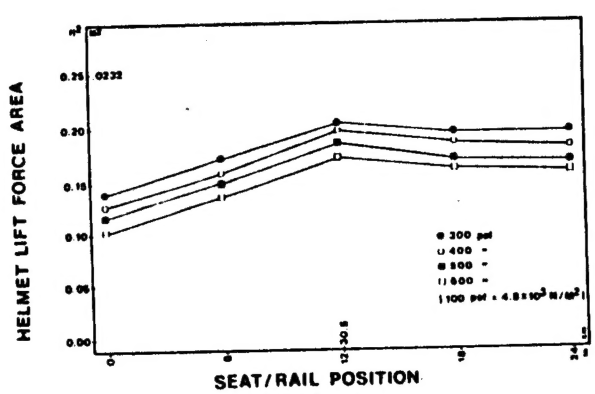

FIGURE 3